

# Observing the shape of nuclei at high-energy colliders

Giuliano Giacalone

Institut für Theoretische Physik (ITP)  
Universität Heidelberg

October 28<sup>th</sup> 2022

[link to PhD thesis](#)



UNIVERSITÄT  
HEIDELBERG  
ZUKUNFT  
SEIT 1386



European Nuclear Physics Conference 2022 (EuNPC 2022)


Oct 24 – 28, 2022  
University of Santiago de Compostela

I studied the connection between low-energy nuclear structure and high-energy nuclear collisions.


**2021: topic has exploded and it is now a rather broad area.**

**ExtreMe Matter Institute EMMI**  
EMMI Rapid Reaction Task Force  
Nuclear Physics Confronts  
Relativistic Collisions of Isobars  
Heidelberg University, Germany, May 30 – June 3 & October 12-14 2022

**Organizers:**  
Giuliano Giacalone  
Jiangyong Jia  
Vittorio Somà  
You Zhou

  
**Deciphering nuclear phenomenology across energy scales**  
<https://esnt.cea.fr/Phoceal/Page/index.php?id=107> Sep 20<sup>th</sup> - Sep 23<sup>rd</sup> 2022  
**Organizers:**  
Giuliano Giacalone (ITP Heidelberg)  
Jean-Yves Ollitrault (IPHT Saclay)  
You Zhou (Niels Bohr Institute)

**Intersection of nuclear structure and high-energy nuclear collisions**  
**Organizers:**  
Jiangyong Jia (Stony Brook & BNL)  
Giuliano Giacalone (ITP Heidelberg)  
Jacquelyn Noronha-Hostler (Urbana-Champaign)  
Dean Lee (Michigan State & FRIB)  
Matt Luzum (São Paulo)  
Fuqiang Wang (Purdue)

Jan 23<sup>rd</sup> - Feb 24<sup>th</sup> 2023  


→ Next Initial Stages conference (Copenhagen, 2023), will have a track related to nuclear structure. First time for a high-energy nuclear conference!

→ Input for Nuclear Physics LRP in the US, [arXiv link](#)

→ Contributed input to NUPECC LRP 2024 [with Y. Zhou (NBI Copenhagen)]

32. Imaging nuclear structure and quark-gluon plasma at the Large Hadron Collider



Submitted

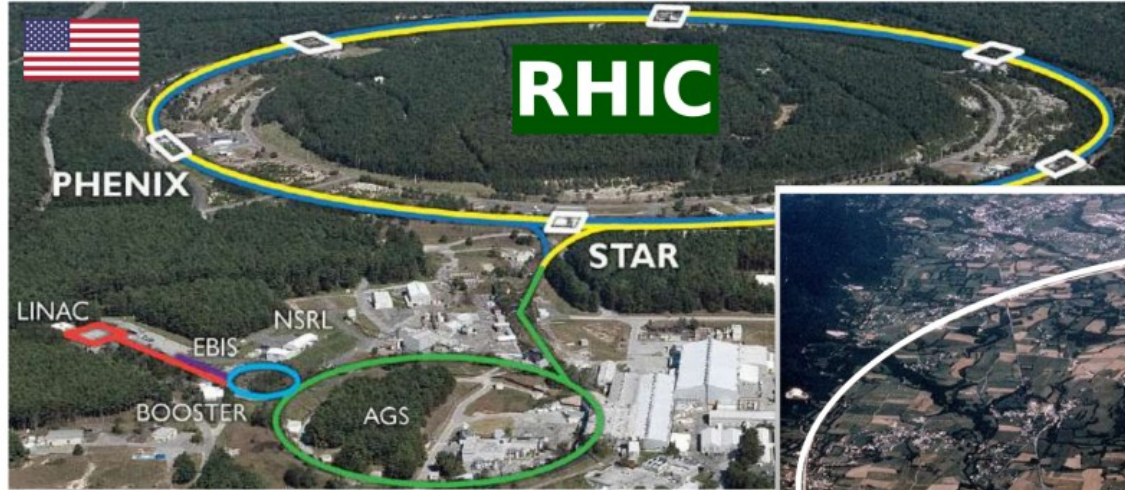
# OUTLINE

- 1 – Nuclear structure input to high-energy nuclear collisions.
- 2 – Nuclear shapes in high-energy nuclear experiments.
- 3 – Prospects.

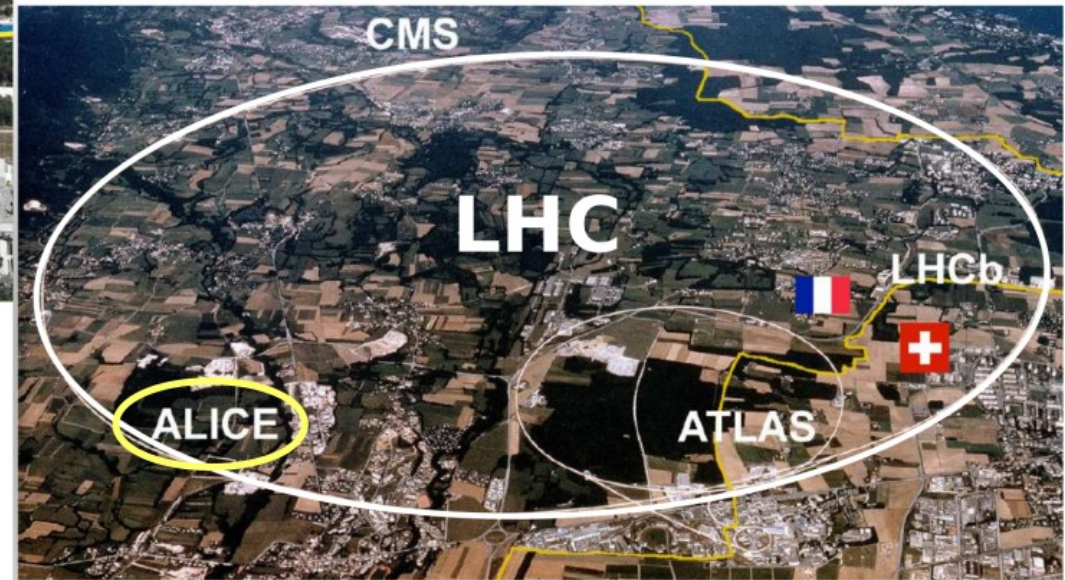
1 – Nuclear structure input to high-energy nuclear collisions.

# HIGH ENERGY NUCLEAR PHYSICS

Long Island (NY)

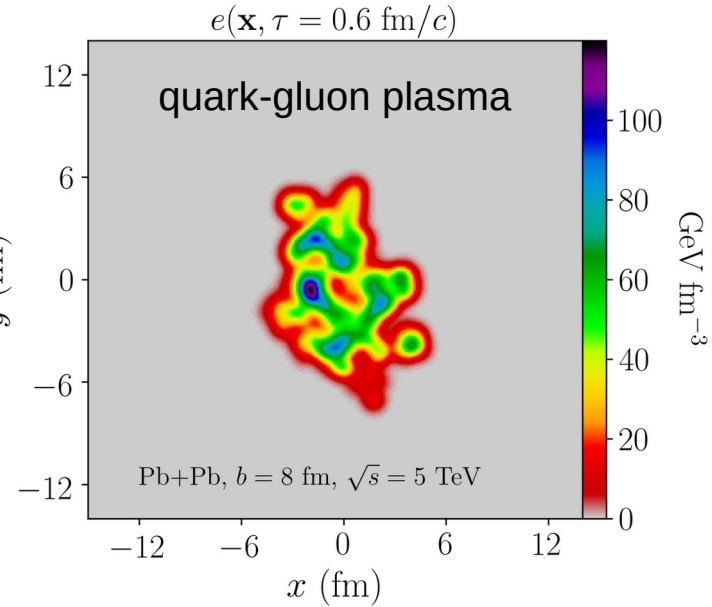
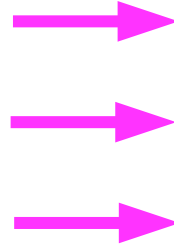
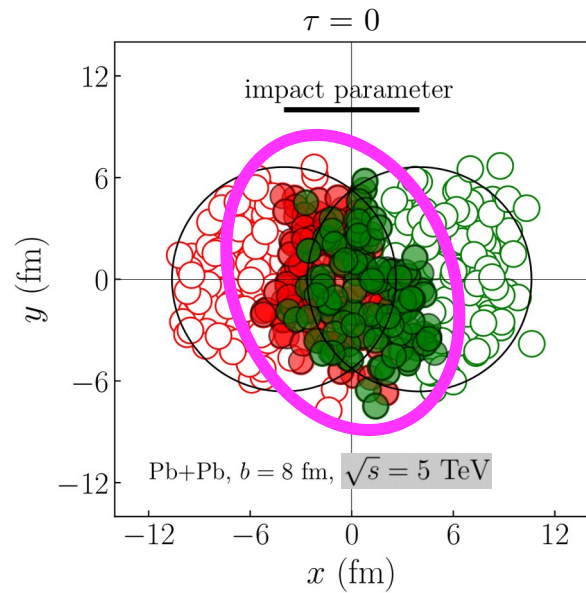


Geneva (CH)



- Great program of high-energy nuclear collisions (~2k experimentalists involved).
- Nuclei collided ~1 month/year @ LHC.
- RHIC is dedicated to nuclear collisions (shutdown ~2026).

# THE EARLY UNIVERSE IN THE LAB



**Effective fluid description:**

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \text{transport}(\eta/s, \zeta/s, \dots)$$

[Romatschke & Romatschke, arXiv:1712.05815]

**Equation of state from lattice QCD. Large number of **DOF** (~40): QGP.**

[HoTQCD collaboration, PRD **90** (2014) 094503]

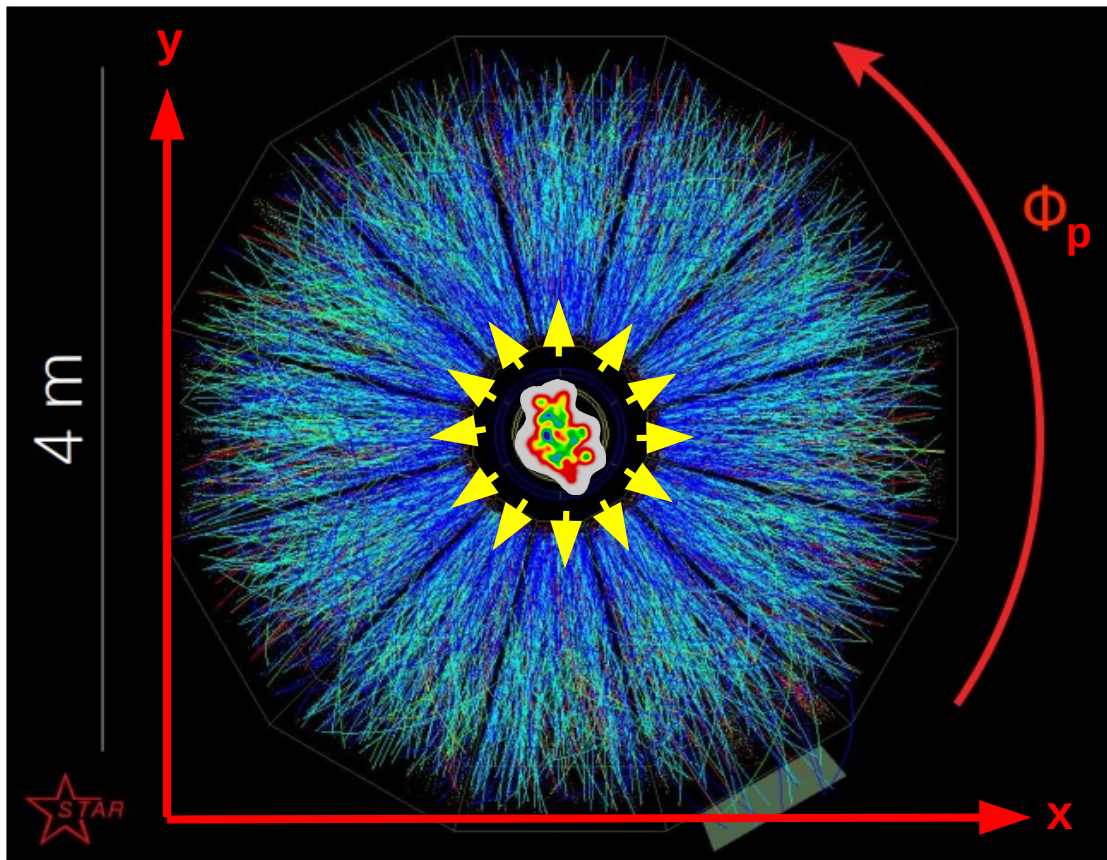
**Relevant temperature at top LHC energy:  $\approx 220$  MeV ( $2.6 \times 10^{12}$  K).**

[Gardim, Giacalone, Luzum, Ollitrault, Nature Phys. **16** (2020) 6, 615-619]

**Main goals: understanding the initial condition and the transport properties.**



# How do we “reconstruct” the QGP from the particle distributions?



All we see is particles.

Hydrodynamics describes the motion of the bulk of these particles.

They sit at low momenta and follow the collective expansion of the system.

$$\frac{d^2 N}{dp_T d\phi} = \frac{dN}{2\pi dp_T} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n) \right)$$

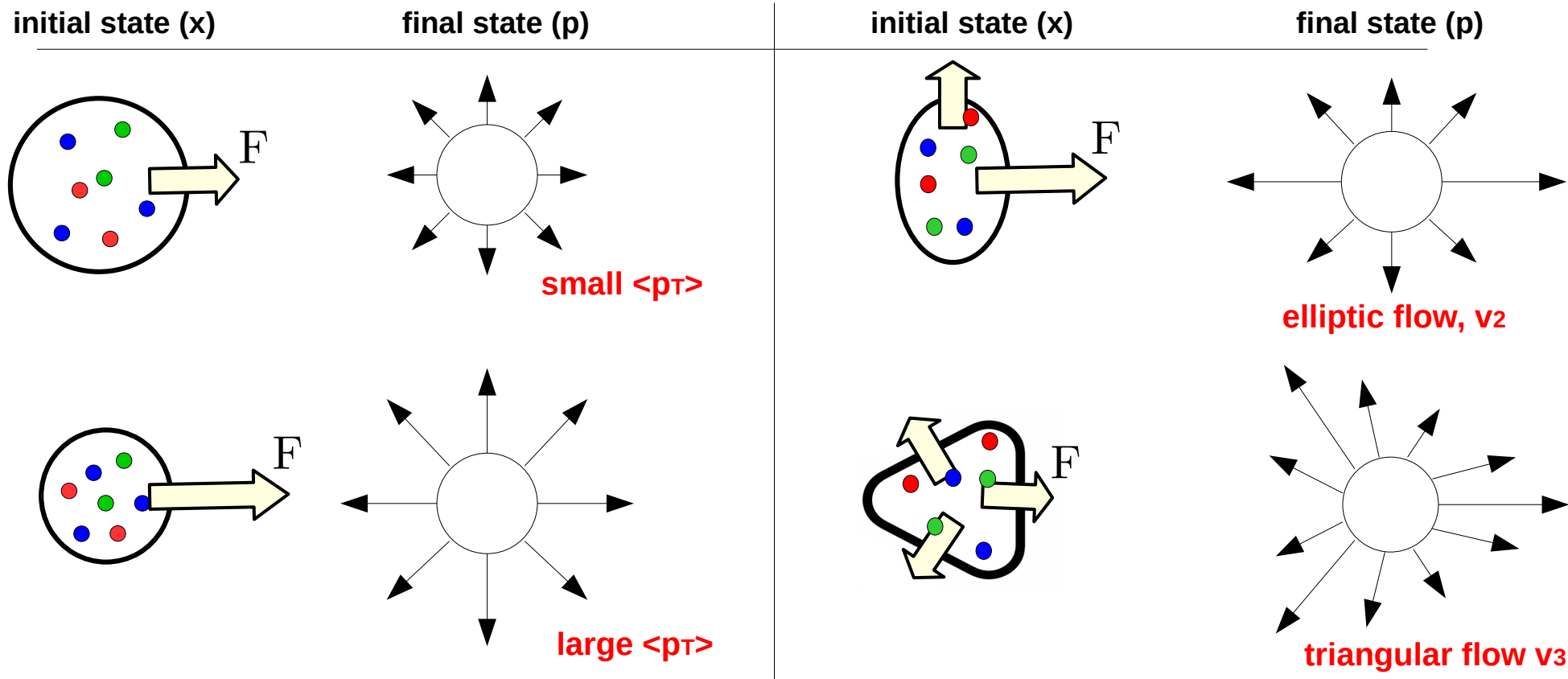
HOW EXPLOSIVE  
IS THE EXPANSION?

IS PARTICLE EMISSION  
ISOTROPIC IN AZIMUTH?

# Mapping initial-state geometry to final-state observables via pressure-gradient force.

$$F = -\nabla P$$

[Ollitrault, PRD 46 (1992) 229-245]

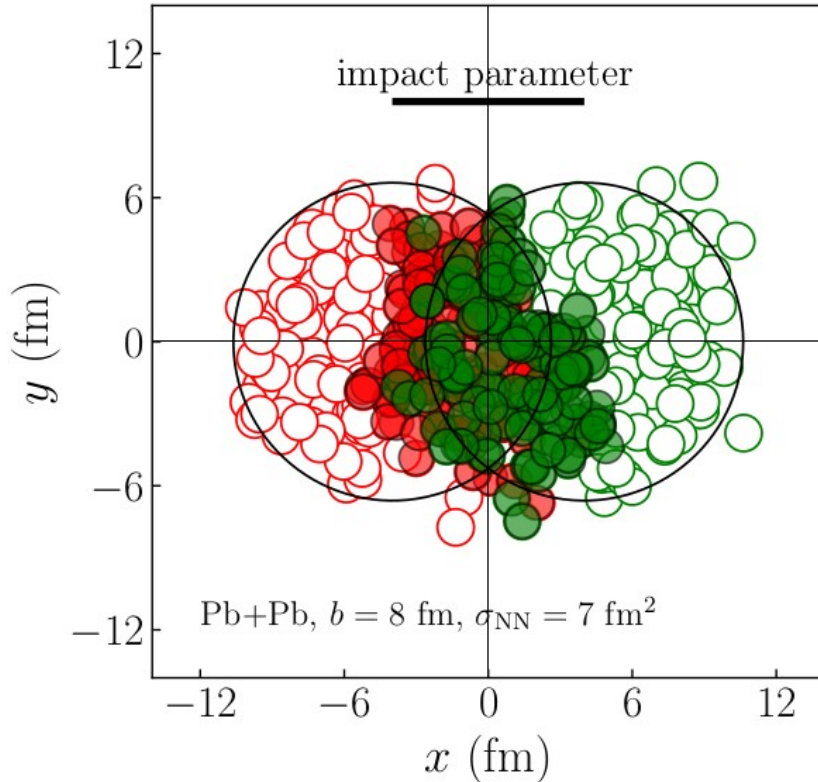


Shape and size of the QGP can be reconstructed from data!



**Formation of QGP starts with an input from nuclear structure.**

**We want to understand this connection from experiments.**



**“Glauber Monte Carlo” approach.**

**Gluons mainly live within nucleons.**

**Interaction is a “quantum measurement” of the positions of the nucleons.**

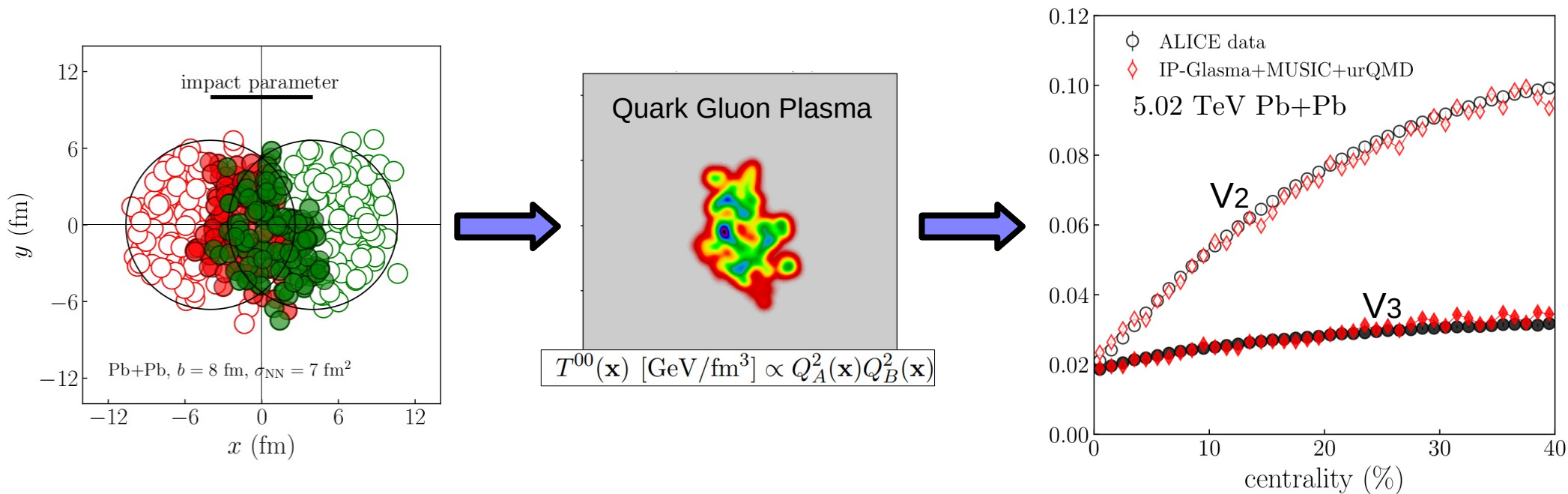
**Collapse of nuclear wave functions.**

**For “spherical” systems like  $^{208}\text{Pb}$ , independent sampling in common potential (mean field) is appropriate.**

$$V(r_i) = -\frac{V_0}{1 + \exp\left(\frac{r_i - R}{a}\right)}$$

Picture fully established in two decades of phenomenological studies.

Hydrodynamic model of heavy-ion collisions is today a precision tool.



## Nuclei are in general strongly-correlated systems:

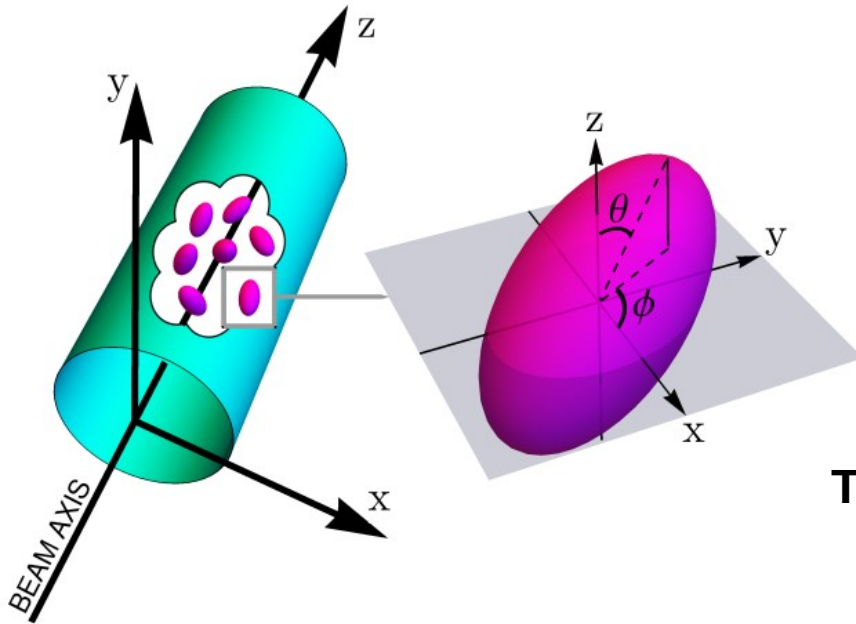
Describing heavy-ion collisions requires *a priori* knowledge of A-body correlation functions, e.g.,

$$\rho_k^{\text{JMNZ}}(\vec{r}_1, \vec{r}_2, \vec{r}_3, \vec{r}_4) \equiv \langle \Psi_k^{\text{JMNZ}} | c^\dagger(\vec{r}_1) c^\dagger(\vec{r}_2) c(\vec{r}_3) c(\vec{r}_4) | \Psi_k^{\text{JMNZ}} \rangle \quad \text{2-body correlation function}$$

## Help from low-energy nuclear physics:

Spatial correlations can be conveniently encapsulated in “intrinsic shapes”.

Instead of A-body correlation functions, use 1-body density with a deformed shape.

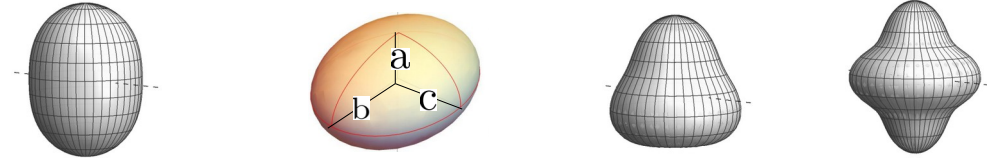


**The nucleus is a deformed bag of nucleons with a random orientation.**

**The interaction selects one such orientation.**

# Generalize the Woods-Saxon profile to include intrinsic deformations:

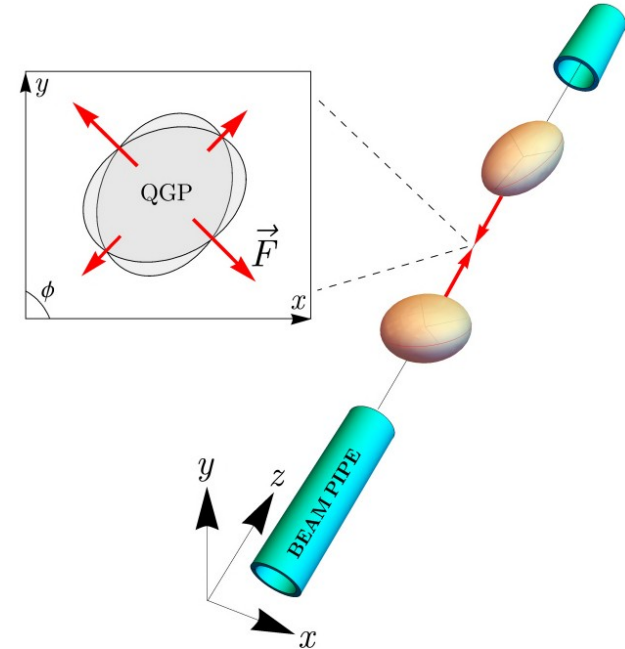
$$\rho(r, \Theta, \Phi) \propto \frac{1}{1 + \exp([r - R(\Theta, \Phi)]/a)} , \quad R(\Theta, \Phi) = R_0 \left[ 1 + \beta_2 \left( \cos \gamma Y_{20}(\Theta) + \sin \gamma \underline{\beta_2} Y_{22}(\Theta, \Phi) \right) + \underline{\beta_3} Y_{30}(\Theta) + \underline{\beta_4} Y_{40}(\Theta) \right]$$



Intrinsic nuclear shapes leave fingerprints  
in essentially all nuclear phenomena.



**THEY SHOW UP AS WELL AT HIGH ENERGY**



2 – Nuclear shapes in high-energy nuclear experiments.



Species that have been collided so far (excludes p-A, d-A, He-A):

**LHC**

@ 2.76-5.02 TeV

- 208Pb, main species → “spherical baseline”
- 129Xe, data released in 2018

**RHIC**

@ 200 GeV

- 197Au, main species
- 238U, data released in 2015
- 96Ru, 96Zr, data released in 2021
- (- 62Cu, very old data set)

→ deformed ions

New questions to address:

Testing high-energy model via crosscheck of nuclear deformation effects.

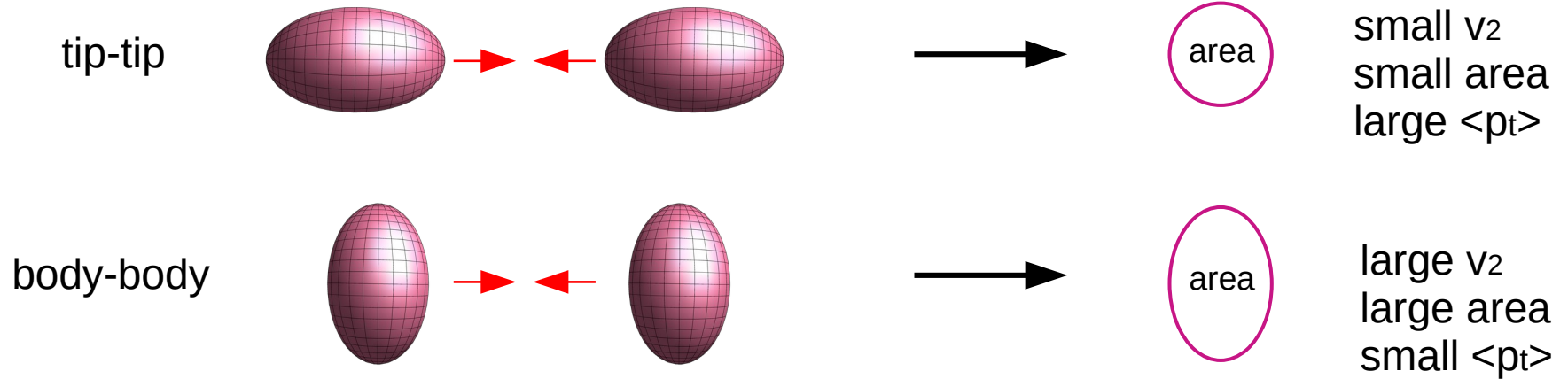
Are low-energy expectations compatible with high-energy observations?

## HOW TO DO THAT? BEST PROBE IS SHAPE-SIZE CORRELATION.

A new “classical phenomenon”.

[Giacalone, PRL **124** (2020) 20, 020301]

[Giacalone, PRC **102** (2020) 2, 024901]



### CENTRAL COLLISIONS OF DEFORMED IONS

**PROLATE**   **OBLATE**

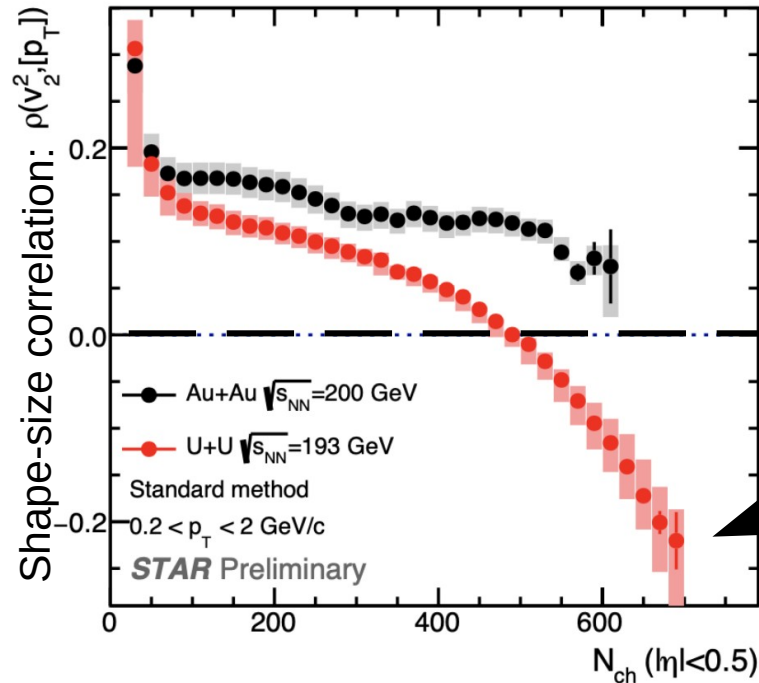
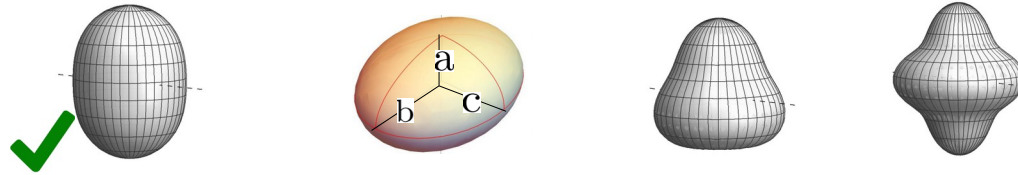
The ellipticity of the quark-gluon plasma is positively/negatively correlated with its area.

**PROLATE**   **OBLATE**

Deformation yields a negative/positive correlation between  $v_2$  and the  $\langle p_t \rangle$ .

# Signature of the strong prolate deformation of uranium-238.

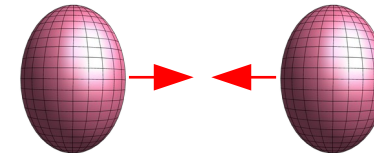
$$R(\Theta, \Phi) = R_0 \left[ 1 + \underline{\beta_2} \left( \cos \gamma Y_{20}(\Theta) + \sin \gamma Y_{22}(\Theta, \Phi) \right) + \underline{\beta_3} Y_{30}(\Theta) + \underline{\beta_4} Y_{40}(\Theta) \right]$$



For prolate deformation:

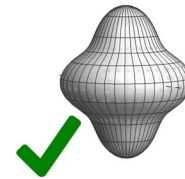
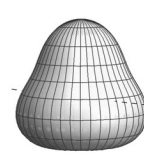
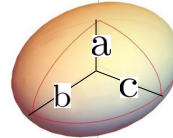
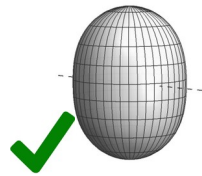
Shape is correlated with size  
 $v_2$  is anti-correlated with  $\langle p_t \rangle$

Limit of fully-overlapping  
 shapes.



# Signature of the hexadecapole deformation of uranium-238.

$$R(\Theta, \Phi) = R_0 \left[ 1 + \underline{\beta_2} \left( \cos \gamma Y_{20}(\Theta) + \sin \gamma Y_{22}(\Theta, \Phi) \right) + \underline{\beta_3} Y_{30}(\Theta) + \underline{\beta_4} Y_{40}(\Theta) \right]$$



**Recently pointed out by W. Ryssens (Brussels).**

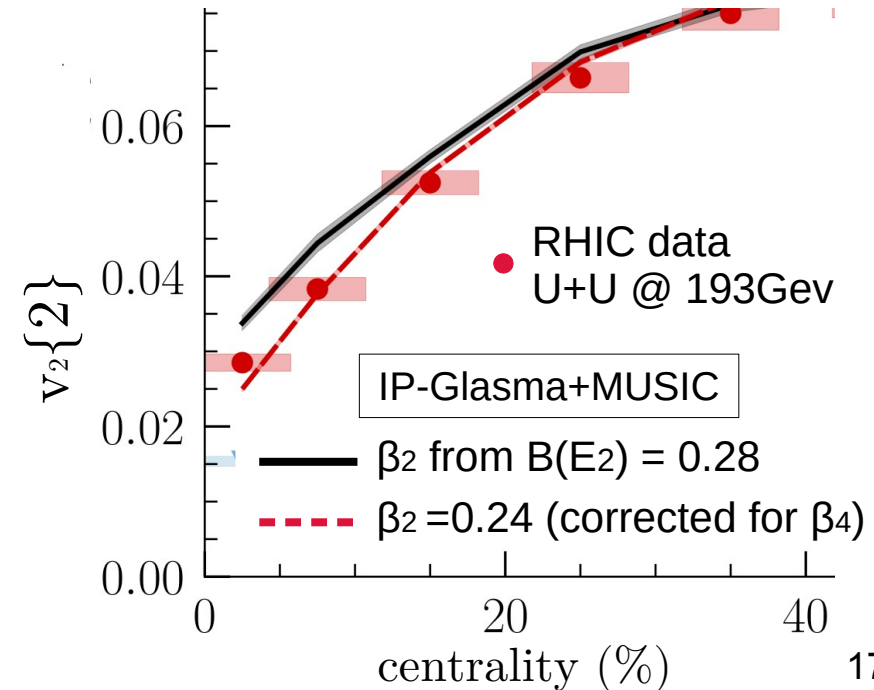
For large quadrupole deformation, coupling with hexadecapole adds a substantial correction.

$$\beta_2 = \beta_2^{\text{WS}} + \mathcal{O}[a] + \mathcal{O}[(\beta_2^{\text{WS}})^2] + \underline{\mathcal{O}[\beta_4^{\text{WS}} \beta_2^{\text{WS}}]}$$

Quadrupole-hexadecapole coupling effectively resolves problems with the description of U-U data.

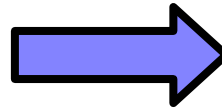
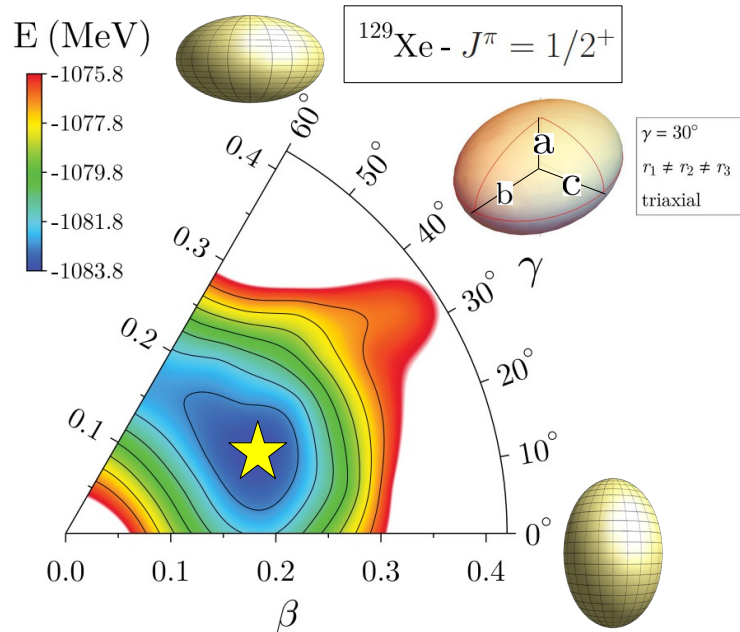
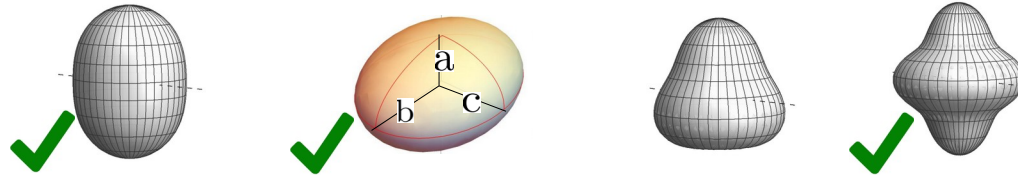
[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]

[Giacalone, Ryssens, Schenke, Shen, in preparation]



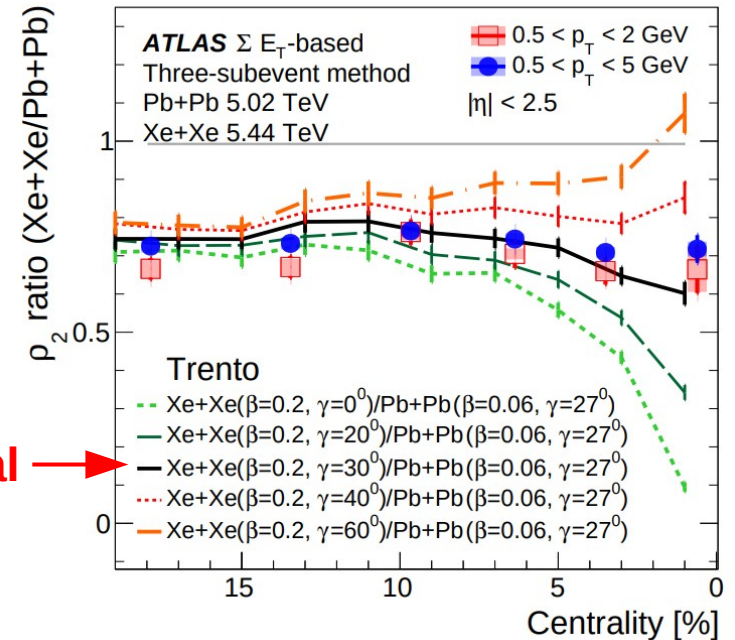
# Signature of the triaxial deformation of xenon-129.

$$R(\Theta, \Phi) = R_0 \left[ 1 + \underline{\beta_2} \left( \cos \gamma Y_{20}(\Theta) + \sin \gamma Y_{22}(\Theta, \Phi) \right) + \underline{\beta_3} Y_{30}(\Theta) + \underline{\beta_4} Y_{40}(\Theta) \right]$$



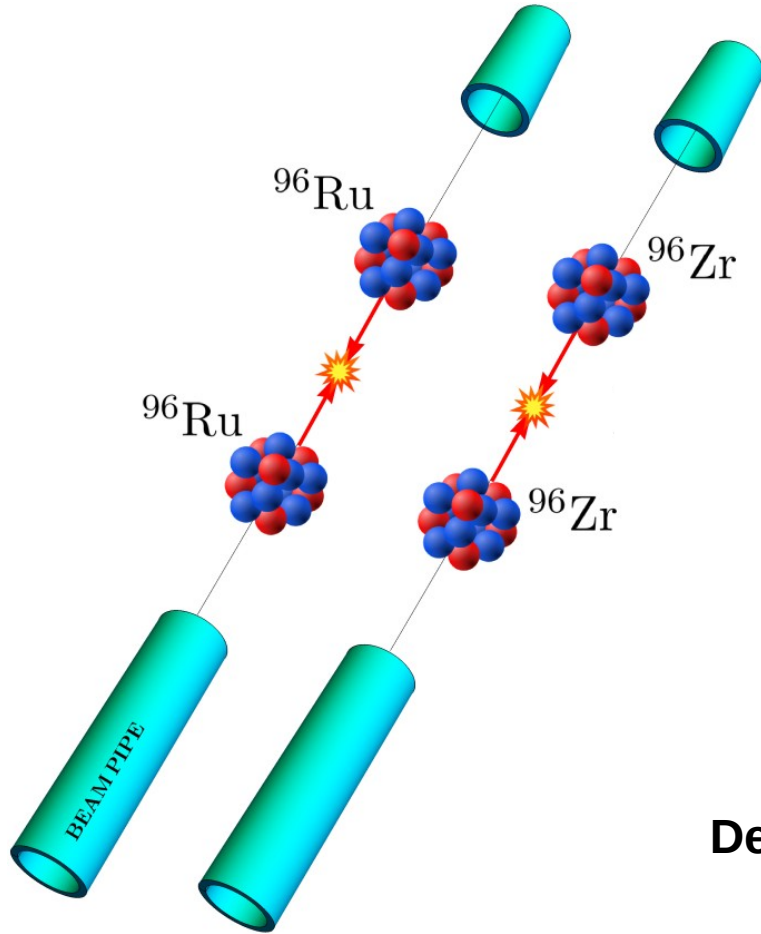
triaxial →

[ATLAS collaboration, arXiv:2205.00039]





## Breakthrough of 2021: data from “isobar collisions” is released.



X and Y are isobars.

X+X collisions produce QGP with same properties as Y+Y collisions.

***Ratios of observables (O) should be unity...***

$$\frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \stackrel{?}{=} 1$$

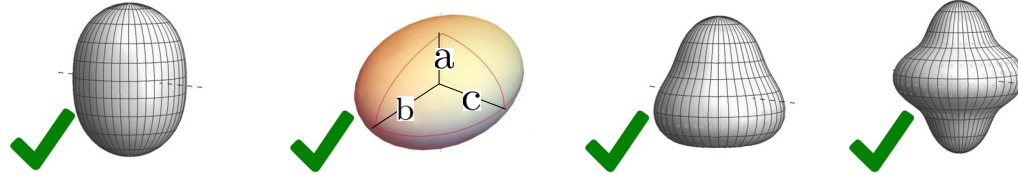
[STAR collaboration, PRC **105** (2022) 1, 014901]  
[Giacalone, Jia, Somà, PRC **104** (2021) 4, L041903]

**Departure from unity is due to nuclear structure.**

**Extremely precise measurements.**

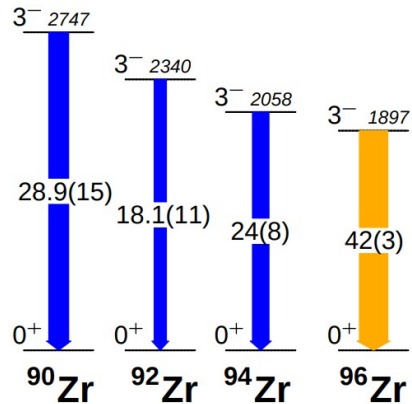
## Signature of the octupole deformation of zirconium-96.

$$R(\Theta, \Phi) = R_0 \left[ 1 + \underline{\beta_2} \left( \cos \gamma Y_{20}(\Theta) + \sin \gamma Y_{22}(\Theta, \Phi) \right) + \underline{\beta_3} Y_{30}(\Theta) + \underline{\beta_4} Y_{40}(\Theta) \right]$$

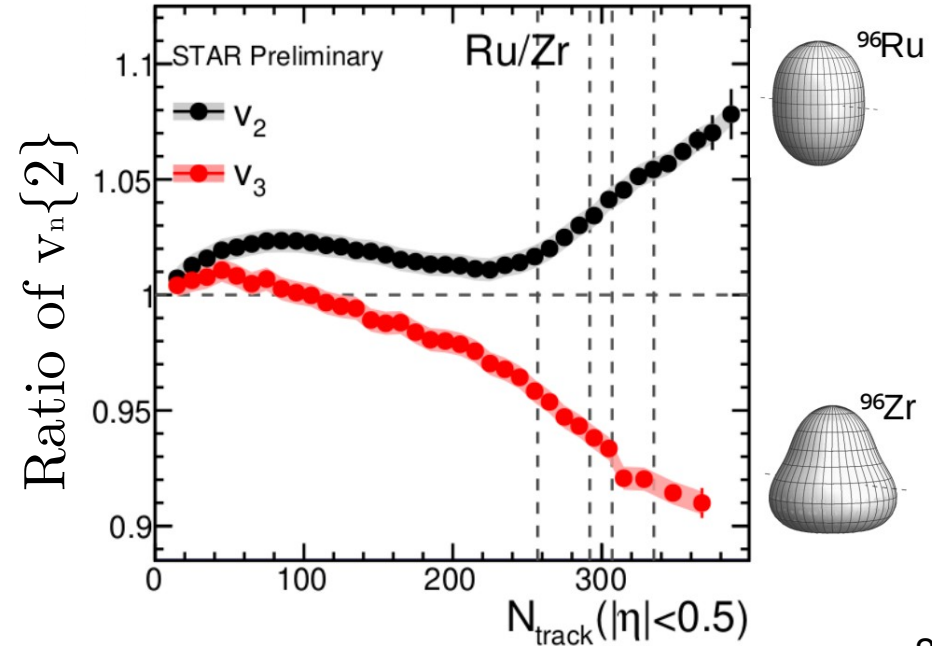


## Signature of octupole deformation.

Octupole deformation of  $^{96}\text{Zr}$  expected from low-lying first  $3^-$  state.



[from M. Zielinska, ESNT workshop]

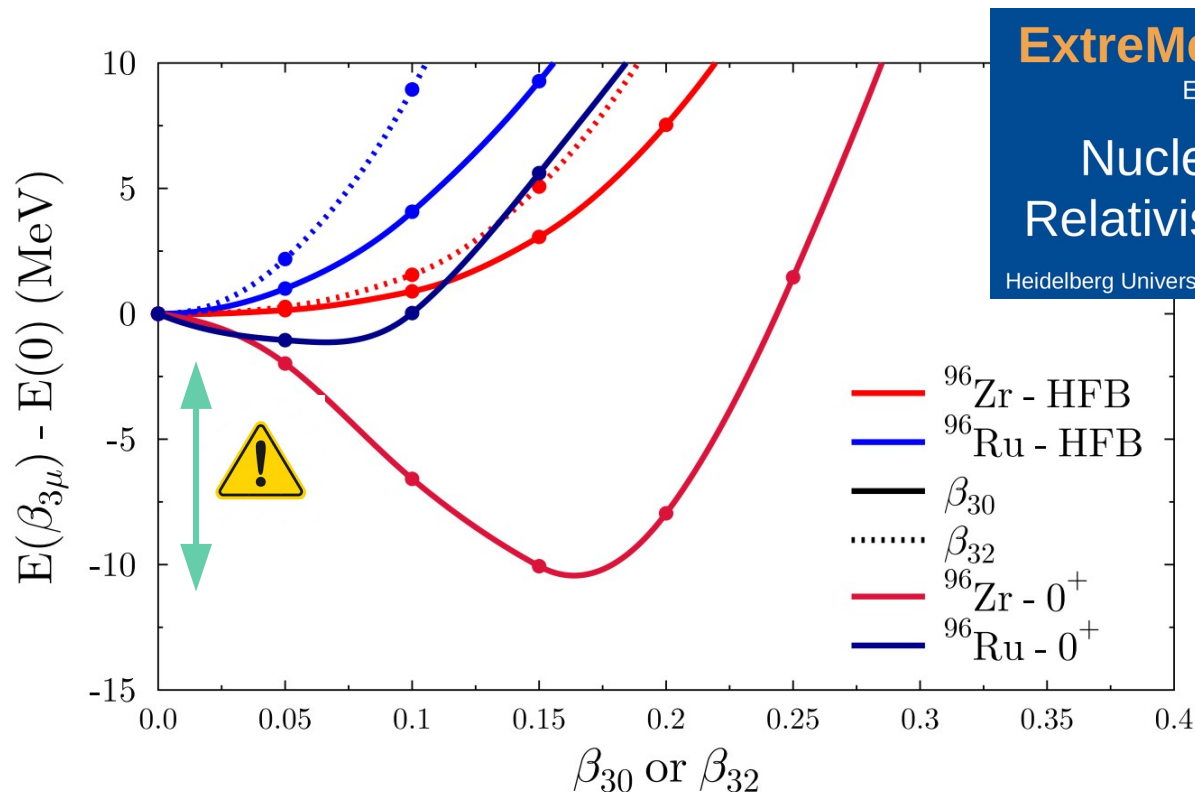


Very clean manifestation at RHIC.

# Does nuclear structure theory explain this quantitatively?

## Octupole deformation is a beyond-mean-field effect.

[Robledo, J.Phys.G **42** (2015) 5, 055109]



**ExtreMe Matter Institute EMMI**

EMMI Rapid Reaction Task Force

**Nuclear Physics Confronts  
Relativistic Collisions of Isobars**

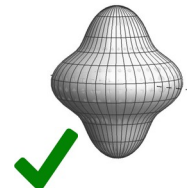
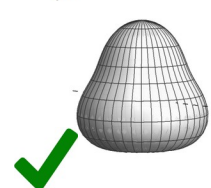
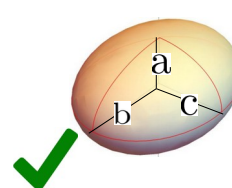
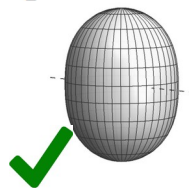
Heidelberg University, Germany, May 30 – June 3 & October 12 – 14, 2022

***Ab-initio* PGCM**  
**Benjamin Bally (Paris-Saclay)**  
**preliminary results**

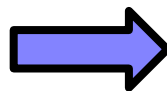
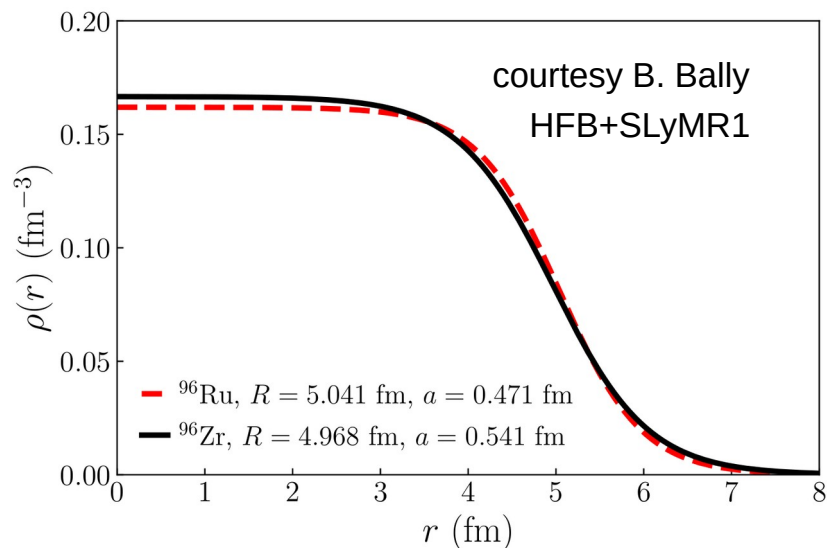
**Preliminary work confirms the large octupole deformation. Large energy coming from projection.**  
**New challenges for nuclear structure theory?**

## BONUS: Signature of skin differences between isobars.

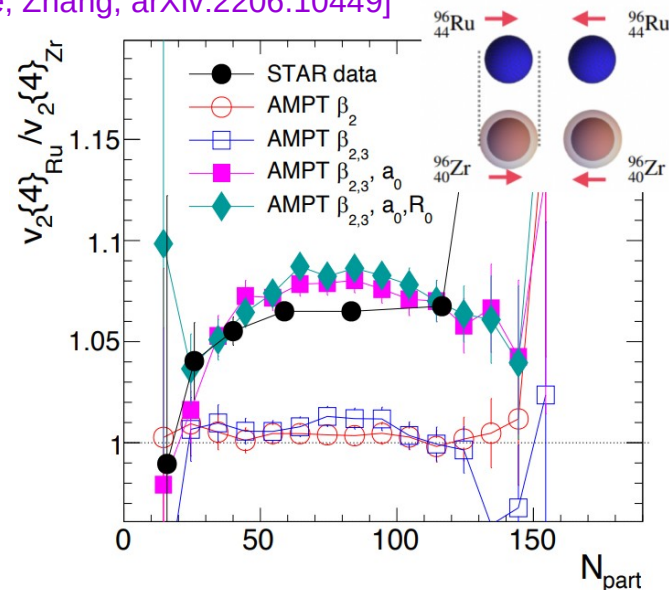
$$\rho(r, \Theta, \Phi) \propto \frac{1}{1 + \exp([r - R(\Theta, \Phi)]/a)} \quad , \quad R(\Theta, \Phi) = R_0 \left[ 1 + \underline{\beta_2} \left( \cos \gamma Y_{20}(\Theta) + \sin \gamma Y_{22}(\Theta, \Phi) \right) + \underline{\beta_3} Y_{30}(\Theta) + \underline{\beta_4} Y_{40}(\Theta) \right]$$



- $^{96}\text{Zr}$ , more diffuse **due to larger N**.
- $^{96}\text{Ru}$ , sharper surface.



[Jia, Giacalone, Zhang, arXiv:2206.10449]



**We can isolate the difference,  $\Delta a$ .**

see also [Nijs, van der Schee, arXiv:2112.13771]  
[Xu et al., arXiv:2111.14812] [Xu et al., PLB **819**, 136453 (2021)]

## Answers to the initial questions:

- All expectations from low-energy nuclear physics are confirmed in high-energy data.
- Quadrupole, triaxiality, octupole (?), hexadecapole, radial profile differences between isobars.
- **Confidence that high-energy model is appropriate.** ✓
- **No clear indication of modifications of nuclear geometry from enhanced gluon fluctuations (Lorentz boost).** ✓



## 3 – Prospects

## Determination of nuclear structure parameters within high-energy model.

From isobars, ratios of observable have simple scaling with parameters.  
Ratios of several observables will pin down parameter differences.

$$\frac{\mathcal{O}_{Ru}}{\mathcal{O}_{Zr}} \approx 1 + c_0(R_{0,Ru} - R_{0,Zr}) + c_1(a_{0,Ru} - a_{0,Zr}) + c_2(\beta_{2,Ru}^2 - \beta_{2,Zr}^2) + c_3(\beta_{3,Ru}^2 - \beta_{3,Zr}^2)$$

[Jia & Zhang, arXiv:2111.15559]

This generalizes to any isobars, or pairs of nuclei close in mass.

In addition, extract nuclear structure from Bayesian analyses of high-energy data.

[see e.g. Matt Luzum, ESNT workshop]

$$\Pr(p \& D) = \Pr(p) \times \Pr(D|p) = \Pr(D) \times \Pr(p|D)$$

prior  $\times$  likelihood = evidence  $\times$  posterior

Promote deformations and skin parameters as model parameters.

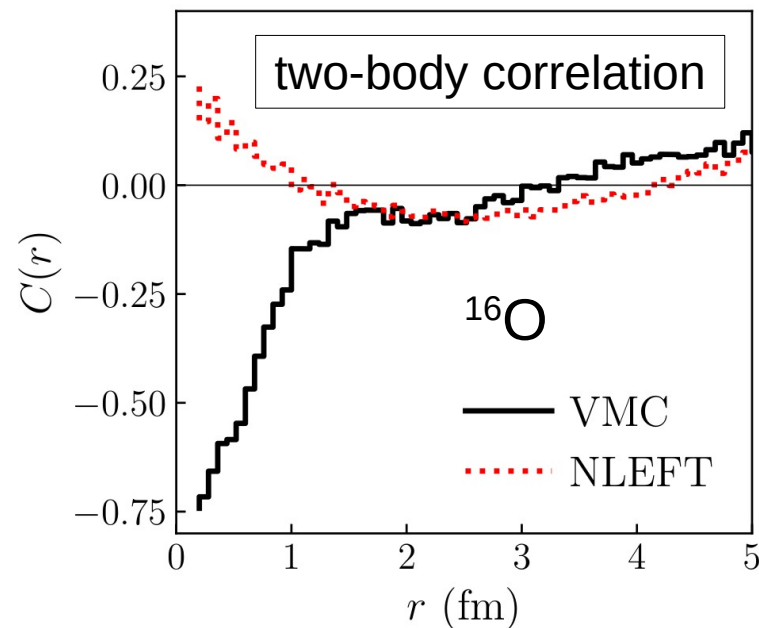
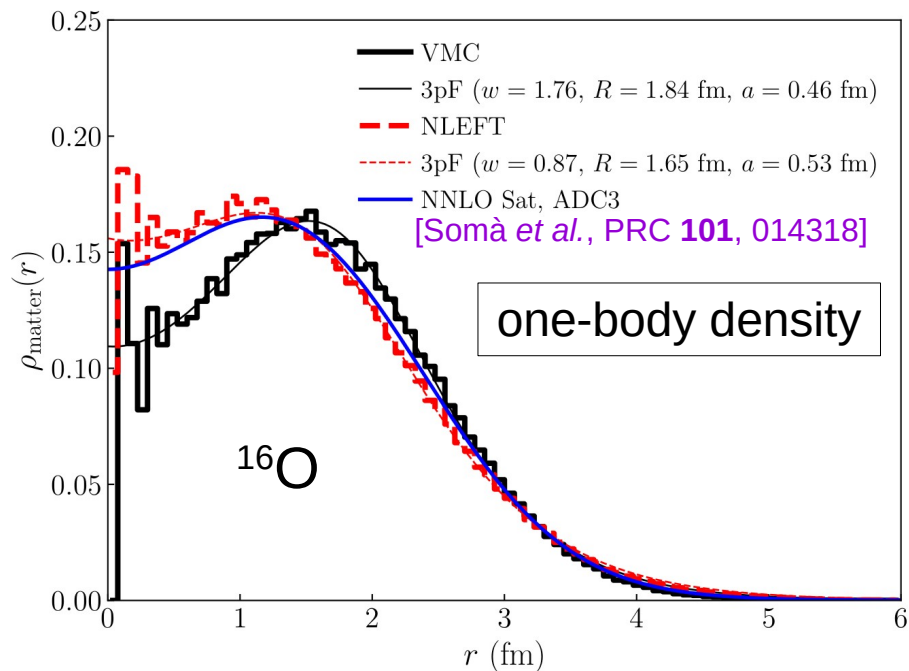
Strong dependence of observables implies posterior distribution can be extracted.

## Going beyond shapes: connection with *ab initio* approaches. Oxygen-oxygen collisions are ideal for the purpose.

- 6000 configurations from **cluster Variational Monte Carlo (VMC)** simulations.  
Interaction: AV18+UIX with a repulsive core. [Londardoni *et al.*, PRC **96** (2017) 2, 024326]

- 15359 configurations from **Nuclear Lattice Effective Field Theory (NLEFT)**.  
Interaction: pionless chiral EFT. Pin-hole algorithm to determine nucleon positions.

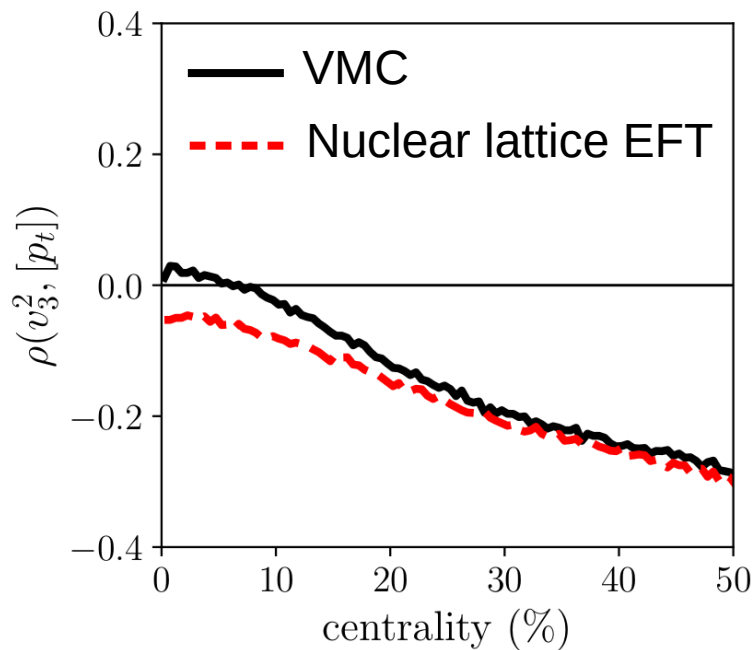
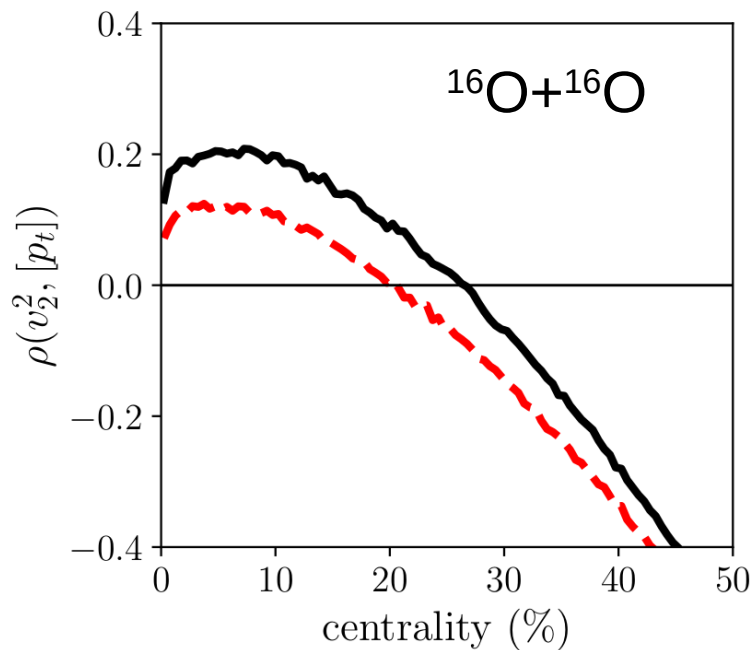
[Summerfield *et al.*, PRC **104** (2021) 4, L041901]



# Study of shape-size correlations in oxygen collisions.

Different predictions from different frameworks... why?  
Different interaction or many-body solution? Role of short-range physics?

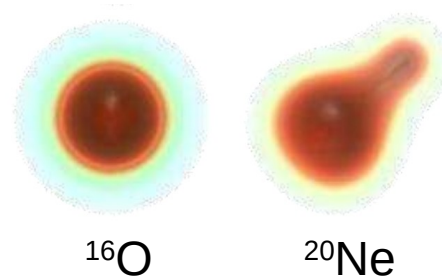
[Giacalone, Nijs, van der Schee, in preparation]



**Precision expected from a short O+O run will resolve the difference.**

**A new tool to test effective theories of QCD for nuclei.**

# Neon-neon collisions to complete small system program at LHC?



$$dN/dy \sim 100$$

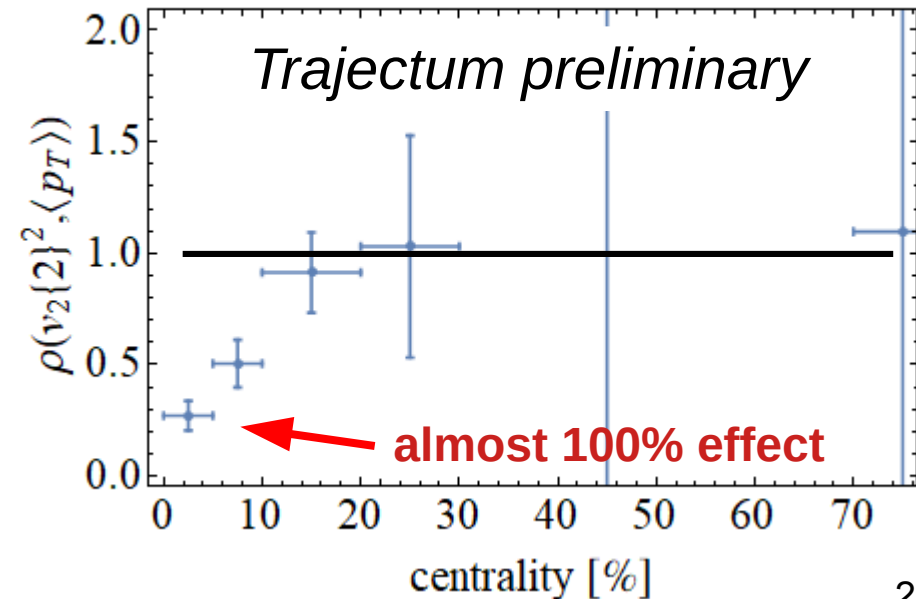
**Strong geometry effects in a small system.**

Extreme structure to test hydrodynamic response.



Nucleus amenable to *ab-initio* description.

Ratio  $^{20}\text{Ne}+^{20}\text{Ne} / ^{16}\text{O}+^{16}\text{O}$



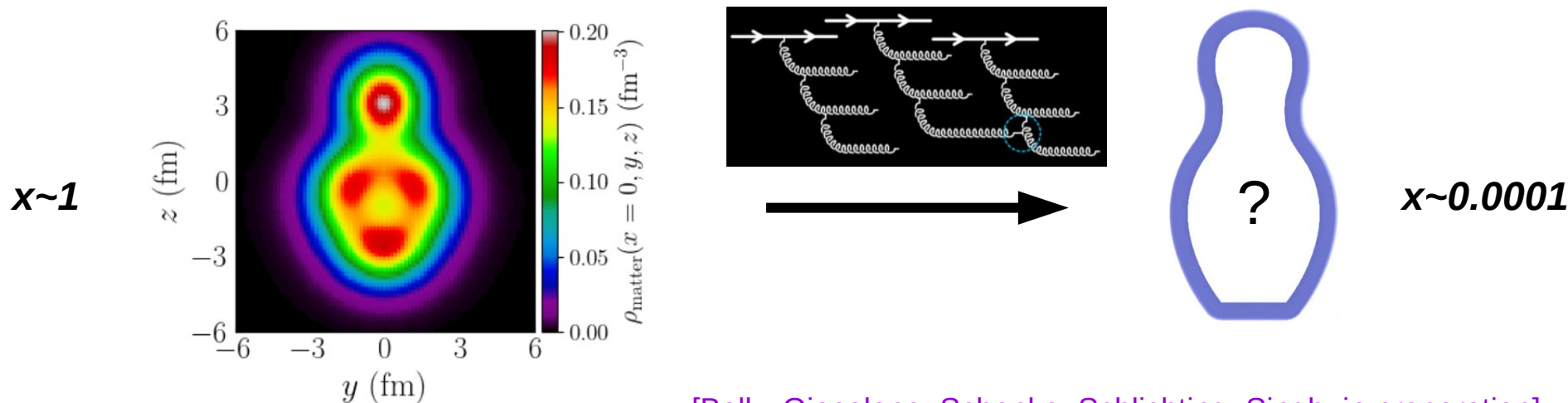
[Giacalone, Nijs, van der Schee, in preparation]



## Longitudinal structure and beam-energy dependence.

Neon-20 is a strongly-correlated system (highly-deformed and clustered).

**Impact of small- $x$  evolution? Melting of clusters?**



[Bally, Giacalone, Schenke, Schlichting, Singh, in preparation]

- 1 – FOCAL upgrade of ALICE. “Dilute-dense” Ne+Ne, one small- $x$ , one large- $x$ .
- 2 –  $^{20}\text{Ne}$  is available in SMOG system of LHCb. Collider + fixed-target means we have collisions at  $\sqrt{s}=7000$  GeV and  $\sqrt{s}=70$  GeV at the same time. Factor 100!

**Window onto the role of quarks and gluons (QCD) for nuclear structure.**

## Possibility of collisions of additional species @ LHC Run 5 and Run 6?

Maximizing impact for both low- and high-energy communities?

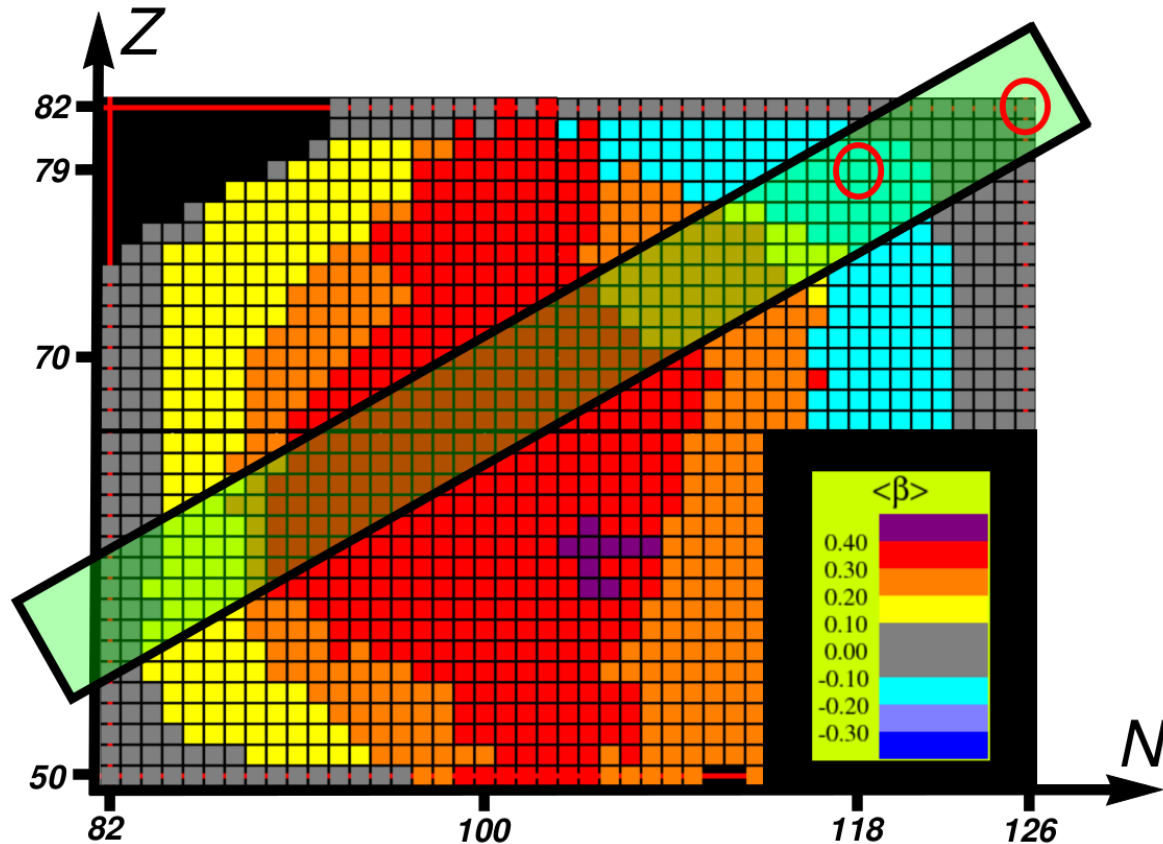
[from Alexander Kalweit,  
ESNT workshop]

<https://indico.cern.ch/event/1078695/>

Nucleon-nucleon luminosity: $\mathcal{L}_{NN} = A^2 \cdot \mathcal{L}_{AA}$	optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
	$\langle \mathcal{L}_{AA} \rangle (\text{cm}^{-2} \text{ s}^{-1})$	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
	$\langle \mathcal{L}_{NN} \rangle (\text{cm}^{-2} \text{ s}^{-1})$	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
	$\mathcal{L}_{AA} (\text{nb}^{-1} / \text{month})$	$1.6 \cdot 10^3$	$3.4 \cdot 10^2$	$3.1 \cdot 10^2$	$8.4 \cdot 10^1$	$3.9 \cdot 10^1$	$2.6 \cdot 10^1$	$5.6 \cdot 10^0$
	$\mathcal{L}_{NN} (\text{pb}^{-1} / \text{month})$	409	550	500	510	512	434	242

# Exploration of rare earth nuclei ... The ultimate nuclear shape experiment?

May be possible only at RHIC, but shut down is imminent.



Anyway, a new method to systematically study strongly-correlated nuclear systems.

# SPECIAL THANKS TO:

- great supervisor: **Jean-Yves Ollitrault (Paris-Saclay)**
- personal guide to nuclear structure physics: **Vittorio Somà (Paris-Saclay)**
- key promoters that have made this research area flourish worldwide:  
**Jiangyong Jia (Stony Brook & Brookhaven)**  
**You Zhou (NBI Copenhagen)**
- many colleagues for their input/collaboration.

# THANK YOU!

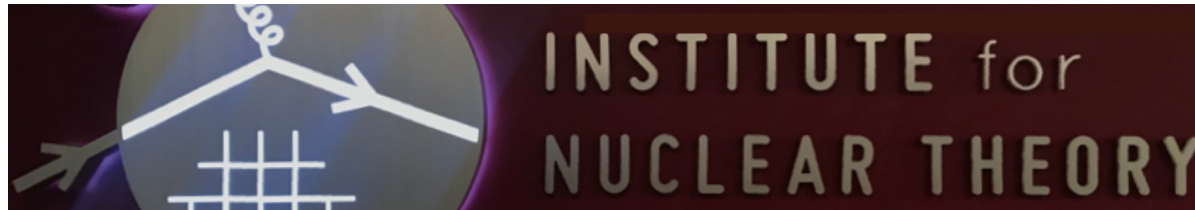
## and stay tuned!

---

**Intersection of nuclear structure and high-energy nuclear collisions**

<https://www.int.washington.edu/programs-and-workshops/23-1a>

**Jan 23<sup>rd</sup> - Feb 24<sup>th</sup> 2023**



**Organizers:**

Jiangyong Jia (Stony Brook & BNL)  
Giuliano Giacalone (ITP Heidelberg)  
Jaki Noronha-Hostler (Urbana-Champaign)  
Dean Lee (Michigan State & FRIB)  
Matt Luzum (São Paulo)  
Fuqiang Wang (Purdue)